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Random discontinuous carbon fibre preforms: Permeability modelling and resin injection simulation

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ABSTRACT

The distribution of fibre bundles in chopped carbon fibre preforms was described using a stochastic model, as a function of geometrical and preform processing parameters. Local permeability distributions were generated from this, based on Gebart's model for the permeability of aligned fibres. Resin injection simulations were evaluated statistically based on these permeability distributions. Results indicate that, as expected, the macroscopic preform permeability decreases with increasing superficial density (i.e. the average fibre volume fraction). It is independent of the tow filament count and the fibre length within the ranges investigated. The observed coefficient of variation of the permeability increases with increasing filament count, fibre bundle length and superficial density. At constant preform superficial density, variation of the preform processing parameters (fibre spray path offset, spray tool elevation, and spray path pattern) affects the fibre bundle distribution and thus the flow front patterns. Different combinations of the processing parameters have different effects on the mould fill times.

1. Introduction

Directed carbon fibre preforming (DCFP) is an automated process for the manufacture of random fibre preforms, which can be used for the production of composite components applying resin injection processes such as resin transfer moulding (RTM). The process typically consists of four main stages: deposition, consolidation, stabilisation and extraction. A robot-mounted mechanical chopper head sprays fibres and a polymeric, powdered binder onto a perforated tool, following a pre-defined deposition path. Air is evacuated from the underside of the tool and the resulting pressure differential holds the deposited fibres in place. When material deposition is complete, a matched perforated tool is lowered to compress the preform to control its thickness. Hot air is cycled through the perforations to activate the binder, and subsequently ambient air is cycled to stabilise the preform. Finally, the preform is extracted from the preforming station and transferred to a separate moulding station for the injection of liquid resin via conventional means. The properties of preforms produced by DCFP are determined by four main factors:

- uniformity of the superficial density
- fibre orientation distribution
- fibre length distribution
- average tow filament count.

Typical applications are in the automotive industry, where DCFP components offer the potential for weight reduction by 40–60% compared to steel components. Cost savings over more conventional processing technologies for carbon fibre composites are significant [1] and may become more so with the introduction of low-cost, high filament count tows (>24 K). The potential of DCFP for structural applications has been investigated within the aerospace industry [2,3] and in large wind turbine applications [4,5]. Various mechanisms have been explored to orient the chopped tows to improve the mechanical properties and to increase fibre volume fractions. However, most result in substantially longer cycle times [6], rendering the methods unsuitable for high throughput applications. Industrial development of this technique continues [7], driven by cost predictions which show that DCFP is cost effective at volumes of up to 50,000 parts per year [8,9].

In recent work, the microstructure of the DCFP preforms was analysed [10], and the effects of fibre length and tow filamentisation on the mechanical properties were investigated in detail [11,12]. The preforms are designed for processing by RTM, but the permeability, which determines the resin impregnation process and thus the production cycle time, is essentially unknown. While a wide variety of experimental and theoretical studies on the permeabilites of fibrous reinforcements, such as textile fabrics and random mats, have been published, none of the results are directly applicable to DCFP preforms. The preform structure differs significantly from that of textile fabrics, since the chopped fibre bundles are oriented randomly and the fibre lengths are finite.

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On the other hand, the filaments are clustered in fibre bundles, resulting in properties which are expected to be different from those for random filament mats. The only published data on the permeability of this type of reinforcement was found in a recent study by Merhi et al. [13]. They investigated the through-thickness permeability of chopped fibre bundles with elliptical cross-section at a given filament count and fibre length and derived an empirical equation for permeability estimation. However, for the manufacture of automotive closure panels, which typically have shell-like geometries with relatively thin wall thickness (<3 mm), the in-plane permeability of the preforms is generally considered to be more relevant than the through-thickness permeability.

This study aims to characterise the in-plane permeability of chopped carbon fibre preforms and to correlate the permeability with the geometrical preform structure. As in previous studies [14,15], the approach is based on the calculation of local porosity and permeability values from the local fibre bundle distributions. The global flow behaviour for linear resin injection is simulated in a cavity with constant height, considering the random nature of the fibre bundle arrangement. Probable outcomes of resin injections and the global permeability value and its variance are deduced from statistical evaluation of the simulation results.

2. Modelling

2.1. Preform structure

A simulation tool has been developed to describe the influence of both fibre and process related parameters on the geometrical structure of DCFP preforms. The fibre bundles are characterised by the filament count c_f, the length l, the linear density λ (a function of the filament count) and the width w. While the actual bundle cross-sections typically show characteristics of elliptical, lenticular and almost rectangular shapes, here they are assumed to be flat (rectangular) and are characterised by a "bundle superficial density"

$$S_0 = \frac{\lambda}{w}. \tag{1}$$

Both w and S_0 are assumed to be independent of the bundle compression, which results from the closure of the mould tool. A robot spray path is defined to manufacture a rectangular flat preform with dimensions L_x and L_y along the coordinate x- and y-directions. The required number of robot sweeps along the x-axis is

$$N_s = \frac{L_y}{\Delta y}, \tag{2}$$

where L_y is the preform width and Δy the spray path offset, i.e. the distance between sweeps. The mass of fibre required for each sweep to fulfil the superficial density requirements S_t of the preform is

$$m_s = \frac{S_t L_x L_y}{N_s}. \tag{3}$$

Therefore, the length of fibre deposited per sweep,

$$l_s = \frac{m_s}{\lambda}, \tag{4}$$

can be determined from the linear density of the chosen roving. The time it takes for the robot to complete one linear sweep is

$$t_s = \frac{L_x}{v_r}, \tag{5}$$

where v_r is the robot speed. Thus, the linear speed at which the fibre tows leave the chopping apparatus is

$$v_t = \frac{l_s}{t_s}. \tag{6}$$

The linear fibre speed is subsequently used to calculate the number of tow segments leaving the apparatus per second

$$\frac{dN_t}{dt} = \frac{v_t}{l}. \tag{7}$$

At a given robot speed v_r, the time step between deposition of tow segments,

$$\Delta t_r = \left(\frac{dN_t}{dt}\right)^{-1}, \tag{8}$$

allows discrete locations along the spray path for the chopper apparatus to deposit fibres to be determined. A virtual circle (Fig. 1) is drawn at each robot location to depict the base of the spray cone, where the diameter is a function of the tool elevation Δz and robot speed v_r. The number of tows deposited within each circle depends on the number of tows being processed simultaneously by the apparatus. The polar coordinates of the centroid of each deposited tow i are determined by a random angle θ_i and radius R_i. θ_i has values between 0 and 2π, and R_i is the product of a random number returned from a normal distribution (mean 0 and standard deviation 0.5) and the diameter of a virtual circle, which has been observed experimentally to enclose 95% of tow centroids at given Δz and v_r. The tow orientation α_i about its geometric centre, relative to the coordinate x-axis, is determined by an additional random number between 0 and π.

The preform is discretised along the coordinate x- and y-directions into a grid of $n_x \times n_y$ square cells with edge length L (Fig. 2). Once the simulation of the spray deposition process is complete, the number of fibre bundles, N, and the orientations of the fibre bundles, α_i, are determined at the centroid of each cell and written to a text file for further processing.

2.2. Local permeability

For each cell of the discretised preform structure, the local fibre volume fraction V_f is determined from N according to

$$V_f = \frac{N S_0}{h\rho}, \tag{9}$$

where S_0 is defined according to Eq. (1), ρ is the density of the fibre material and h is the cavity height. This implies the assumption that the filaments are distributed evenly across the cavity height. Realistically, if the uncompressed height of N fibre bundles is smaller than the cavity height, it is more likely that zones of high filament den-

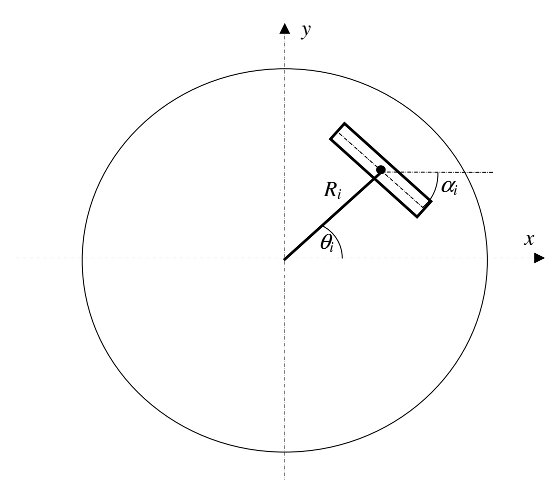

Fig. 1. Virtual circle depicting the base of the spray cone; θ_i and R_i describe the position of the centroid of tow i, α_i describes the tow orientation.